

Servo system, apparatus comprising a servo system, sigma delta modulator, and integrated circuit comprising a sigma delta modulator

The invention relates to a servo system for generating a normalized digital actuator-signal from first and second control signals, said servo system comprising a sigma delta modulator for generating a digital representation of the quotient between the difference and the sum of the two control signals. Furthermore the invention relates to an apparatus 5 comprising a servo system, a sigma delta modulator, and an integrated circuit comprising a sigma delta modulator.

Such a servo system is known from applicant's prior European patent 10 application publication 0 501 570. Servo systems often generate an actuator signal from the difference ($P - Q$) of two control signals P and Q . Sensors generate the two control signals and the purpose of the servo system is to control an actuator into the position wherein the sensors produce equal control signals. In this position the difference signal is zero while it is negative at one side of this position and positive at the other side of this position. However, 15 in many servo systems the amplitude of the control signals is not only dependent on the error to be corrected but also on other, desired or undesired, parameters. For instance, in optical recording, the control signals P and Q are derived from signals generated by several segments of a photodiode and the amplitude of these signals is proportional to the output power of the laser and the reflection of the optical disc. Therefore, the signals are modulated by the 20 information on the disc. Furthermore disc reflection variation across the surface of the disc and, more important, across different disc manufacturers must be compensated for. This is done by normalizing the control signals, i.e. by dividing the control signals or the difference between the control signals, by the sum of these control signals.

The general form of the normalization is given by $(P - Q)/(P + Q)$. The control 25 signals P and Q themselves may be derived from different combinations of the photodiode-segment signals, dependent on which parameter has to be controlled e.g. focus, track following etc. The division of the difference signal $P - Q$ by the sum signal $P + Q$ is often implemented by using a so-called Gilbert cell. This implementation makes use of the fact that there exists an exponential relation between the collector current and the base-emitter voltage

of bipolar transistors. However, presently there is a trend to minimize the number of ICs and therefore to move the normalization function into a CMOS IC (Complementary Metal-Oxide-Semiconductor Integrated Circuit). In such ICs the MOS-transistors have a square or substantially square characteristic of drain current versus gate-source voltage, so that the
5 Gilbert topology cannot be used. European patent application publication referenced above shows a solution that allows the use of MOS transistors for dividing the difference signal $P - Q$ by the sum signal $P + Q$. Herein a digital sigma-delta modulator is used with a digital low-pass filter followed by a quantizer whose output is fed back to the input of the low-pass filter. This solution consists in having a digital multiplier in the feedback path between the
10 output of the quantizer and the input of the low-pass filter of the sigma-delta modulator, while the digital sum signal is used as the multiplication factor for the digital multiplier. It can be shown that with this arrangement the quantizer output is a digital signal whose value is substantially equal to the ratio of the input value to the sigma-delta modulator and the input value to the feedback multiplier.

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It is an object of the present invention to use the same principle as is used in the aforementioned prior art document but with substantially reduced circuit components and/or chip area (integrated circuit area). To this end the servo system of the present
20 invention is therefore characterized in that the sigma-delta-modulator is an analog sigma-delta-modulator having an analog low-pass filter, a quantizer arranged for receiving an output signal of the analog low-pass filter, a multiplying DA-converter for converting and multiplying an output signal of the quantizer by the sum of the first and second control signals and means for supplying the difference of the first and second control signals and the
25 output signal of the multiplying DA-converter to an input of the analog low-pass filter.

In the servo system of the prior art document the digital sigma-delta modulator has only one function, namely the normalization of the error correction signal, whereas the digitization of the signals is performed prior to the sigma-delta modulator in multi-bit AD-converters. In contradistinction thereto in the servo system of the present invention the analog
30 control signals are both normalized and digitized in the same analog sigma-delta modulator so that preceding analog to digital converters are economized.

The quantizer of the analog sigma-delta modulator produces digital words of a certain bit-length and of a certain sample rate. The words of the quantizer are used in the multiplying DA converter. Herein each of the bits of the digital word switches a current that

has to be proportional to the "significance" of the respective bit and to the multiplication factor, in this case the sum of the first and second control signals. A very simple implementation is obtained when the servo system of the present invention is further characterized in that the multiplying DA-converter comprises a 1 bit quantizer and a current source supplying the sum of the first and second control signals and switch means controlled by the output signals of the quantizer for switching said current source to the input of the low-pass filter. In this case the quantizer is a simple comparator comparing the output of the low-pass filter with a DC reference level. The multiplying DAC is just one single current source representing the sum ($P + Q$) of the two control signals that is switched on and off depending on the output of the comparator.

In the servo system of the present invention the difference ($P - Q$) between the two analog control-signals is applied to the input of the analog low-pass filter. In CMOS it may be difficult to carry out such subtraction operation. To facilitate this operation the servo system of the present invention may be further characterized in that the analog low-pass filter is a differential analog low-pass filter having a first and a second input terminal to which the first and second control signals respectively are applied. Preferably a current source supplying a control current i_p is connected to one of the inputs of the differential low-pass filter and a current source supplying a control current i_q is connected to the other input terminal of the differential low-pass filter.

The most efficient and convenient implementation of the analog low-pass filter is a first order differential integrator. However, with such kind of low-pass filter the DC impedance at the input terminals is extremely high. When this low-pass filter is driven with current sources, the result is an arrangement in which the DC level at the input terminals is completely floating. This may be overcome when, according to another aspect of the invention, the servo system is characterized by a common mode control circuit for stabilizing the common mode voltage at the input of the differential analog low-pass filter.

With the above-described arrangement the derivation of the sum signal from the two control signals requires good care to prevent DC-offset and gain mismatch to occur. For instance when a DC-offset occurs in the sum signal this will result in an error in the normalization, so that the error correction signal generated by the arrangement becomes dependent on equal amplitude variations of the control signals. Also a gain mismatch may occur in the sum signal, which results in a change in the overall loop gain of the servo system. It is a still further object of the invention to avoid these problems and therefore the servo system of the present invention is further characterized in that the common mode

control circuit is an operational transconductance amplifier (OTA) which receives at its input the mean voltage of the two input terminals of the analog low-pass filter and a reference voltage and whose output constitutes said current source supplying the sum of the first and second control signals. Said mean voltage may e.g. be easily derived from the
5 interconnection of two serially connected equal resistances between the input terminals of the filter. By the feedback loop the output current of the OTA is then equal to the sum of the control currents that are applied to the input of the low-pass filter, so that the abovementioned errors (offset and gain) are automatically avoided. In this sigma delta modulator the sum signal is not applied as a separate input signal but is automatically generated in the sigma
10 delta modulator itself.

When the analog low-pass filter is implemented by a differential integrator, the problem may arise that, even with a common mode control circuit at the input terminals of the filter, the output of this filter, which is connected to the input of the quantizer, is still floating, so that the operation of the quantizer becomes unpredictable. To avoid this the servo
15 system according to the present invention may preferably be characterized in that the analog low-pass filter comprises first and second single-ended integrators for integrating the first and second control signals respectively and an operational transconductance amplifier (OTA) which receives at its input the mean voltage of the two output terminals of the analog low-pass filter and a reference voltage and whose output constitutes said current source supplying the sum of the first and second control signals. Again said mean voltage may be derived from the
20 interconnection of two serially connected equal resistances, in this case between the output terminals of the filter.

25 The invention will be described with reference to the accompanying figures.

Herein shows:

Fig. 1 a servo system according to the invention,

Fig. 2 a first embodiment of a sigma delta modulator according to the invention,

30 Fig. 3 a second embodiment of a sigma delta modulator according to the invention and

Fig. 4 a third embodiment of a sigma delta modulator according to the invention.

Fig. 1 shows a servo system for use in apparatus for optical recording on and/or reproduction from an optical disc. A block R schematically shows the optical system of such apparatus. Particulars of such optical system may be found e.g. in applicant's 5 European patent application publication 0501570 Fig. 9 or in "The Compact Disc Handbook" by Ken C. Pohlmann, ISBN 0-89579-300-8, chapter 4. Both publications are incorporated herein by reference.

The optical system R usually comprises at least one photodiode that receives a light beam reflected from the optical disc and that operates as sensor for the servo system. In 10 the system of Fig. 1 one beam is used that is sent to the disc (not shown) and the reflected beam is sensed by a four-segment photodiode Z. The four segments of the diode Z are denoted by a, b, c and d and they generate signals A, B, C and D respectively. Because the amount of light received by the segments of the photodiode is dependent on the focusing of the beam on the disc and on the tracking of the beam along the tracks of the disc, the signals 15 generated by the photodiode can be used to control the focusing and the tracking.

An adder S₁ generates a control signal P from the segment signals according to the formula $P = A + D$ and an adder S₂ generates a control signal Q according to the formula $Q = B + C$. With the control signals P and Q so composed, the difference signal $P - Q$ could be used to control the focusing of the laser-beam on the optical disc according to the method 20 known as "astigmatic focus error signal generation". However, as explained in the introductory part of this description, it is of primary importance that the error correction signal be normalized to cope with the undesired variations of the control signals P and Q. Therefore, the difference signal $P - Q$ has to be divided by the sum signal $P + Q$ to obtain a normalized error correction signal $(P - Q)/(P + Q)$ for correcting the focus of the laser beam.

25 It may be noted that the same expression $(P - Q)/(P + Q)$ represents a suitable and properly normalized error correction signal for other parameters of the optical system, provided that the control signals P and Q are accordingly composed from the segment signals A, B, C and D. For instance, when $P = A + B$ and $Q = C + D$ the normalized error correction signal $(P - Q)/(P + Q)$ is suitable for guiding the laser beam along the tracks of the optical 30 disc according to the method that is known as "push pull following".

In the arrangement of Fig. 1 the difference signal $P - Q$ is derived in a subtractor S₃ and the sum signal $P + Q$ is derived in an adder S₄. The difference signal $P - Q$ from the subtractor S₃ is applied as input signal to an analog sigma delta modulator M. This analog sigma delta modulator comprises a subtractor S₅, an analog low-pass filter (loop filter)

F for low-pass filtering the output of the subtractor S₅, a one bit quantizer (comparator) E for comparing the output of the loop filter F with a reference voltage and for delivering e.g. a "one" when the output of the loop filter is higher than the reference voltage and a "zero" when this output is lower than the reference voltage and, finally, a multiplying AD converter 5 that multiplies the output pulses of the comparator E with the sum signal P + Q of the adder S₄. The result of this multiplication is subtracted from the difference signal P - Q in the subtractor S₅. In operation: when the low frequency amplification of loop filter F and comparator E is sufficiently high, the feedback loop of the sigma delta modulator makes the low frequency content at the input of the loop filter nearly zero. This means that the two 10 inputs of the subtractor are substantially equal as far as their low frequency contents are concerned. Therefore, the output of the comparator multiplied by the gain factor (P + Q) of the AD converter W equals the input signal (P - Q) or the output signal equals the input signal (P - Q) divided by the sum signal (P + Q). The result at the output O of the analog sigma delta modulator is a one bit digital signal, whose low frequency content is equal to 15 (P - Q)/(P + Q) that can eventually be applied directly or through a suitable analog low-pass filter L to an actuator A_c in the optical system R, for carrying out the required correction. Instead of using the output of the sigma delta modulator to directly drive the actuator A_c, this output may be applied to a decimating filter (not shown) for transforming the error correction 20 signal into a multi bit digital signal that allows the application of various digital signal-processing functions, such as flexible filtering and security measures. The digital error correction signal is subsequently converted into an analog signal for application to the actuator.

Fig. 2 shows an implementation of the sigma delta modulator M with the P - Q subtractor S₃ integrated therein. Because currents can easily be added by connecting 25 the sources together, the control signals P and Q and the sum signal P + Q of Fig. 1 are applied in the form of currents from current sources i_p, i_q and i_{p+q}. Because in CMOS it may be difficult to make subtractions, the loop filter F and the comparator E are of differential nature. A subtraction can now be implemented by simply connecting the current to be subtracted to the other input terminal of the loop filter. So the current source i_p is connected 30 to one of the input terminals of the loop filter and the current source i_q is connected to the other input terminal. The quantizer (comparator) E is clocked with pulses from a clock-pulse generator C₁, which ensures that the quantizations are made at fixed intervals. The multiplying AD converter comprises of a simple differential switch comprising two PMOS transistors W₁ and W₂ whose source electrodes are connected together to the current source

i_{p+q} and whose gate electrodes are connected to the differential output of the comparator E. The drain electrodes of the PMOS transistors W_1 and W_2 are connected to the input terminals of the loop filter F. It may be observed that in this implementation the two filter input terminals serve as both the subtractor S_3 and the subtractor S_5 of Fig. 1. In Fig. 2 a first order 5 low-pass filter is shown but this filter can be made of higher order, which will increase the resolution of the analog to digital conversion of the arrangement.

In Fig. 2 the loop filter is a differential integrator. The input terminals thereof are completely floating, so that a slight offset in the currents i_p , i_q or i_{p+q} will lead to a drift of the input common mode voltage. To prevent this the sigma delta modulator of Fig. 2 10 comprises a common mode control circuit C_m . This circuit contains three NMOS cascodes T_1-T_4 , T_2-T_5 , and T_3-T_6 . Each of the upper transistors has a DC current source I_1 , I_2 , I_3 connected to the respective drain electrode, while the source electrode of each upper transistor is connected to the drain electrode of the corresponding lower transistor and the drain electrodes of T_5 and T_6 are interconnected. The gate electrodes of the three upper 15 transistors are connected to the drain electrode of transistor T_1 . The gate electrode of transistor T_4 is connected to a reference voltage, the gate electrode of transistor T_5 is connected to the drain electrode of transistor T_2 and to one of the input terminals of the loop filter and the gate electrode of transistor T_6 is connected to the drain electrode of transistor T_3 and to the other input terminal of the loop filter. The currents of the current sources I_1 , I_2 and 20 I_3 are preferably equal. The same holds for the three upper transistors and also for the three lower transistors. The three lower transistors have such low drain voltages that they work in their linear range. Therefore, they serve as controlled source resistors for the upper transistors. When the voltages at the two filter input terminals equally increase, the transistors T_5 and T_6 will show a lower resistance in comparison to T_4 . A higher current will flow 25 through T_2 and T_3 and this will restore the nominal situation. Consequently, the common mode control circuit shows low impedance to common mode voltage changes at the filter input terminals. A differential voltage at these terminals will increase the current in one of the transistors T_5 , T_6 but decrease the current equally in the other transistor, so that the common mode control circuit shows high resistance to differential voltages.

30 In Fig. 1 the adder S_4 is arranged to make the sum signal $P+Q$ out of the two control signals P and Q. Similarly, in Fig. 2 the current i_{p+q} has to be made out of the two control currents i_p and i_q . This operation may cause errors such as DC offset or gain mismatch with the result that either the normalization will be disturbed or the loop gain of the servo system will be affected. In the implementation of Fig. 3, in which elements

corresponding with those of Fig. 2 have the same references, the addition of the control currents i_p and i_q to i_{p+q} may be carried out without substantial errors while, moreover, the common mode control circuit C_m of Fig. 2 can be dispensed with. To this end the arrangement of Fig. 3 comprises an operational transconductance amplifier (OTA) with a differential amplifier of two PMOS transistors T_7 , T_8 , a common current source I_4 delivering current to the source electrodes of the two transistors and a current mirror of two NMOS transistors T_9 , T_{10} for mirroring the drain current of PMOS transistor T_7 . Furthermore, two equal resistors R_1 and R_2 are connected in series between the input terminals of the differential loop filter F and the connection point of these resistors is connected to the gate electrode of T_8 while the gate electrode of T_7 is connected to a reference voltage V_r . The interconnected drain electrodes of the transistors T_8 and T_{10} constitute the output of the OTA and this output is connected to the two source electrodes of the differential switch transistors W_1 and W_2 . In operation: because of the equality of the resistors R_1 and R_2 the interconnection of these resistors has the common mode voltage of the two filter input terminals. The feedback loop of the OTA through the current mirror transistors T_9 , T_{10} and the differential switch transistors W_1 , W_2 , maintains this interconnection at the reference voltage V_r of the gate electrode of transistor T_7 . Therefore the OTA prevents floating common mode voltages at the filter input terminals and therefore the unit C_m of Fig. 2 has become superfluous. What is more: the current supplied by the OTA to the interconnected source electrodes of the differential switch transistors W_1 and W_2 is equal to the sum of the two control currents i_p and i_q , provided that the resistors R_1 and R_2 are sufficiently equal and of sufficiently high value. Then any offset and gain mismatch errors in the generation of the sum current i_{p+q} are avoided.

Capacitive feed through of the switching signals from the comparator in the switches W_1 and W_2 may occur. The resulting charge injection at the input of the filter F leads to inaccurate normalization especially for small input currents i_p and i_q . The problem may be overcome by dummy transistors (capacitors) that are connected with shorted drain and source between the gate electrode of each of the transistors W_1 , W_2 and the drain electrode of the other of these transistors. The same measure may be taken in the arrangements of Figs. 2 and 4.

When the differential loop filter F is an integrator the output terminals thereof are for DC completely separated from the input terminals by the feedback capacitors. When, moreover, the clocked comparator E does not clamp the common mode voltage at its input terminals, this voltage is completely floating. Consequently an additional common mode loop

to control the output of the loop filter is needed. However, the problem can be solved in the manner depicted in Fig. 4. In this Figure circuit elements that correspond with circuit elements of Fig. 3 have the same reference numerals.

The differential integrator F of Fig. 3 is now replaced by two single ended
5 integrators G_1 and G_2 , each comprising an operational transconductance amplifier (OTA) O_1 and O_2 respectively and an integrating capacitor between the output and the inverting input of the OTA. These inverting inputs are also connected to the control current sources i_p and i_q while the non-inverting inputs of the two OTAs are connected to a reference voltage V_{r1} . A third operational transconductance amplifier O_3 has its non-inverting input connected to the
10 interconnection of two equal resistors R_3 and R_4 , which are serially coupled between the outputs of the two OTAs O_1 and O_2 . The inverting input of O_3 receives a reference voltage V_{r2} and the output of this OTA delivers the current i_{p+q} to the source electrodes of the differential switch transistors W_1 and W_2 . The single loop through O_1 , O_2 , resistors R_1 , R_2 ,
15 the OTA O_3 and the differential switch W_1 , W_2 keeps the common mode voltage of the input terminals of O_1 and O_2 at the reference potential V_{r1} and of the output terminals of O_1 and O_2 at the reference potential V_{r2} . The resistors R_3 and R_4 may be connected to the output terminals of OTAs O_1 and O_2 through buffer stages (not shown) to prevent that too high value resistors have to be used. The same measure may be taken for the connection of the resistors R_1 and R_2 to the input terminals of the differential filter F in Fig. 3.